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Strategic Opportunities in Implementing Industry 4.0 for Natural Fiber- Reinforced Polymer Composites

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Abstract

*Cyber-physical systems (CPS) lie at the heart of the fourth industrial revolution, more widely recognized as **Industry 4.0**. This emerging paradigm is characterised by the seamless and instantaneous integration of physical and digital systems, creating an interconnected environment where machines, data, and human intelligence work in close collaboration. The proposition behind Industry 4.0 suggests that the fusion of advanced digital technologies with traditional industrial processes will fundamentally transform the nature of work. As a result, it will bring about a revolutionary shift in the way tasks are organised, managed, and executed across diverse sectors. In the proposition, it is suggested that the instantaneous integration of physical and digital systems, in conjunction with new technologies that facilitate work, will revolutionise the ways of work and, as a result, the process of work management. This customary trade-offs in operations between the competitive objectives of cost, flexibility, speed, and quality have the potential to be disrupted or, at the very least, altered by this technology, which has the capacity to disrupt them. Traditionally, industries have operated under inherent trade-offs between cost, flexibility, speed, and quality, forcing organizations to prioritize one competitive objective over another. The purpose of this article is to provide a broad overview of the enabling technologies that define Industry 4.0 while also highlighting the opportunities and constraints they present for future research. The primary focus is on industries that are responsible for the production of goods, which includes both the manufacturing and agricultural sectors to some extent. Additive manufacturing, the internet of things, blockchain technology, sophisticated robotics, and artificial intelligence are some of the topics that are explored.*

Keywords: additive manufacturing, information technology, blockchain, robots, artificial intelligence

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INTRODUCTION

Automation, electrification, and computers each propelled significant and revolutionary advancements in the manufacturing of commodities and services. The concept of Industry 4.0, initially introduced by the German economic development agency GTAI, asserts that we are now witnessing the onset of a novel industrial revolution facilitated by the emergence, progress, and convergence of many technologies that allow for a nearly instantaneous link between the physical and digital domains. The integration of digital and physical elements, facilitated by additive manufacturing (AM), the internet of things (IoT), blockchain, advanced robotics, artificial intelligence (AI), and other associated technologies, is a highly influential and extensive phenomenon that will impact all aspects of the factory and the supply chain[1,32]. The technologies fundamental to the concept of Industry 4.0, both individually and collectively, have the potential to decrease costs, increase flexibility, boost speed, and enhance quality. Furthermore, Industry 4.0 presents the opportunity to alleviate the inherent conflicts between these crucial operational priorities. Engaging with Industry 4.0 is crucial for the academic community in operations management (OM). It is imperative from an educational standpoint to provide our students with the necessary information and abilities to effectively handle the forthcoming challenges in operations and supply chain. This study aims to investigate the extent to which the technologies supporting Industry 4.0 pose challenges to our existing knowledge of operations. Furthermore, it seeks to identify the new and significant operational issues that will arise because of the progress and implementation of these technologies. This paper examines different fundamental technologies of Industry 4.0. Its main objectives are to (i) enhance knowledge and comprehension of Industry 4.0 within the operations management community and (ii) promote research in this field by highlighting potential opportunities and obstacles. Given those objectives, we will concentrate our attention on the operational consequences of these fundamental technologies and deliberately exclude the examination of other potentially significant areas, such as medical and financial applications. Moreover, in accordance with the essence of the concept of Industry 4.0, our focus will be on the creation of physical goods rather than the provision of services. Naturally, with the increasing prevalence of product servitization, a phenomenon that is likely to be expedited by Industry 4.0, the differentiation between products and services becomes increasingly indistinct at times. Yet, we specifically exclude the examination of intelligent operations in the public and retail sectors, as these areas are already addressed in other papers within this issue [19,20]. When analysing products production, we consider both the manufacturing and agriculture sectors. As will become evident, Industry 4.0 is not merely a loose term encompassing a range of different technologies. Indeed, the potential of Industry 4.0 lies in the possible interactions and synergies among different components of these technologies. For instance, the progress made in sensors and artificial intelligence has facilitated the creation of collaborative robots that operate in conjunction with humans.

1. Industry 4.0 is transforming natural fiber-reinforced polymer composites (NFRPCs) using AI-driven material informatics, digital twins, and generative design to achieve optimal fiber-matrix selection and lightweight constructions. Advanced manufacturing incorporates 3D printing, IoT-enabled processing, robotics, and closed-loop feedback to guarantee precision and efficiency, while real-time monitoring, predictive maintenance, and AI-based NDT improve performance and dependability. Sustainability is attained through block chain-enabled traceability, digital life cycle assessment, and circular manufacturing, guaranteeing environmentally responsible sourcing and recycling. Collaboration between humans and machines is enhanced by AR/VR training and cloud-based co-design platforms. Applications include lightweight automobile components, sustainable aircraft structures, and smart construction panels with integrated sensors, and biodegradable packaging, establishing NFRPCs as a fundamental element of sustainable, high-performance materials in the Industry 4.0 era.
2. Natural fiber-reinforced polymer composites (NFRPCs) encounter challenges such as fiber variability, moisture sensitivity, and equipment degradation, complicating failure predictions through traditional methods. However, AI-driven predictive maintenance mitigates these issues by employing IoT sensors to continuously monitor machine conditions and fiber quality, while machine learning models identify anomalies, forecast remaining useful life, and enhance processes. This facilitates proactive maintenance, automated operator notifications, and ERP/MES connection, resulting in diminished downtime, enhanced yield and quality, cost efficiency, sustainability, and increased safety. In a compression molding line, AI can identify aberrant pump vibrations, arrange prompt repairs, and modify curing cycles to counteract fiber moisture fluctuations, therefore averting failures and product problems.
3. Smart factories integrate IoT, AI/ML, robotics, digital twins, cloud platforms, and additive manufacturing to revolutionize NFRPC production from inflexible mass manufacture to adaptable, sustainable mass customization. Digital twins provide sector-specific virtual

prototyping—lightweight, crashworthy car panels, moisture-resistant aerospace interiors, and climate-adapted construction beams—while AI-driven robotic layup, adaptive curing, and 3D printing provide on-demand, cost-effective customization at scale. IoT-enabled quality control guarantees defect-free products, while cloud-based configurators allow clients to directly articulate performance requirements, which are promptly transformed into machine instructions. Regional smart factories minimize logistics, emissions, and expenses by procuring natural fibers locally with block chain traceability. The outcome is scalable, robust, and environmentally efficient production that expedites innovation cycles, fortifies supply chains, and promotes the adoption of NFRPCs within the automotive, aerospace, and construction sectors.

4. Almeshaal et. al [3] investigated the Grewia Monticola Sond (GMS) plant bark fibers as potential polymer composite fillers, characterizing their morphological, chemical, and thermal properties using FTIR, XRD, TGA, DSC, AFM, and 13C NMR techniques.
5. According to Palanisamy et. al [38] Hybrid kenaf/banana epoxy composites were studied for wear resistance at fiber loadings of 20–40 wt.% under loads up to 30 N and sliding distances of 75 m, with 40 wt.% showing the best wear performance, confirmed by SEM analysis. Mechanical testing revealed high tensile (~140 MPa) and flexural (>170 MPa) strengths with less than 10% reduction after water saturation, while impact strength showed slightly higher variability. The addition of banana fibers reduced water absorption, making these hybrids promising for wear-resistant applications in high-moisture environments.
6. **Palaniappan** et. al [39] characterized Ficus retusa L. (FRL) aerial root fibers, revealing high cellulose content (64.12%), good crystallinity (CI 55.96%), strong mechanical performance (tensile strength 331–465 MPa, modulus 3.33–5.81 GPa), and excellent thermal stability (up to 527 °C). With low wax content, fine microfibril angle (7.2°), and smooth surface morphology, FRL fibers show strong potential as eco-friendly reinforcements for sustainable composites.
7. **Palaniappan** et. al [40] extracted cellulose from Citrus × sinensis peel waste using chemical treatments, yielding 67.82% with a density of 1.413 g/cm³, high crystallinity (72.54%), and thermal stability up to ~308 °C. Characterized by FTIR, XRD, TGA, DSC, SEM, and elemental analysis, the cellulose showed unique physicochemical and morphological properties, highlighting its potential as a sustainable reinforcement filler for polymer composites.
8. Palanisamy et. al [41] characterized Acacia caesia (Senegalia caesia) bark fibers, showing a density of 1200 kg/m³, composition of 37% cellulose, 20% hemicellulose, and 18% lignin, with thermal degradation onset at 308 °C. While suitable for composite applications, their roughness and tendency to split indicate that treatments are needed to regularize geometry and improve performance as reinforcement fillers.

While acknowledging these synergies, we categorise this paper based on technology and refer to their possible interconnections as required. Presented here is a comprehensive summary, together with the research consequences, of the following technologies: additive manufacturing (Section 2), the internet of things (Section 3), blockchain (Section 4), advanced robotics (Section 5), and artificial intelligence (Section 6). Additional pertinent technologies are briefly addressed in Section 7. Finally, in Section 8, we provide some observations regarding the influence of Industry 4.0 on operations strategy. This article does not aim to provide a comprehensive or representative overview of the emerging academic operation management literature on Industry 4.0. Therefore, any publications cited are not meant to be exhaustive or representative.

OBJECTIVES

1. To understand the readiness of industries especially in manufacturing for Industry 4.0 integration.
2. To propose strategic measures and research areas to overcome identified challenges and promote sustainable Industry 4.0 adoption.

Research Methodology

Data Collection

Review of scholarly journals, industry reports, and white papers on Industry 4.0 technologies and practices.

Scope

Focus primarily on the **manufacturing** sectors of Natural Fiber- Reinforced Polymer Composites.

Basic Terminologies

Additive Manufacturing

Additive manufacturing (AM), or three-dimensional (3D) printing, is a robotic technique that generates physical objects by sequentially adding tiny layers of material from a computer 3D model. Despite the existence of several additive manufacturing (AM) technologies such as material jetting, powder bed fusion, and vat polymerisation, the fundamental process flow of these technologies remains consistent. The original 3D digital model is transformed into a digital.stl file format and thereafter visually divided into a series of flat horizontal-layer models. The digitally sliced layers serve as the guiding instructions for the additive manufacturing "machine" to systematically create the product, layer by layer. In many cases, a last stage is necessary after the removal of the object from the machine. Additive manufacturing (AM) has been widely recognised as a groundbreaking technology that has significant implications for operations management. Why? Let us examine the core operating objectives of quality, adaptability, efficiency, and cost. Additive manufacturing (AM) allows for the creation of intricate forms and interior structures that cannot be achieved with conventional manufacturing techniques. Additive manufacturing (AM) addresses the manufacturability limitations that design engineers encounter when developing items whose performance quality is influenced by shape. One well-known instance is the fuel nozzle used in GE's LEAP aeroplane engine. Engineers at GE devised a novel nozzle tip design that played a crucial role in enhancing fuel efficiency, but found a drawback. The detailed internal geometry of the tip was excessively intricate and nearly unattainable to fabricate [8, 26]. Nevertheless, GE successfully developed the new design utilising additive manufacturing (AM) technology. Currently, the company produces the nozzles using large-scale AM at a facility located in Alabama. An additive manufacturing (AM) machine is agnostic to the specific shape it is programmed to create. Consequently, it does not need a new configuration when transitioning between producing products with quite diverse geometries. Subject to spatial limitations, certain additive manufacturing machines have the capability to concurrently manufacture many things. Inherently flexible, additive manufacturing (AM) technologies have the potential to eradicate industrial diseconomies of variation at their theoretical limit. The process of new product design is iterative, in which preliminary designs are improved through prototype testing. Commercial production commences once the design has been completed. Due to the time-consuming nature of prototype production using conventional manufacturing techniques, commercial production may necessitate the creation of specialised tooling and equipment tailored to the product. Due to its flexibility, additive manufacturing (AM) enables quick prototyping and eliminates the need for waiting for product-specific resources in commercial production. Consequently, the speed to market is significantly improved. Due to comparable factors, the initial production costs are also decreased as there is no need for investments in product-specific industrial processes. Holding all other factors constant, a lower initial cost decreases the sales volume needed to reach the breakeven point, therefore enabling the profitable manufacture of low volume products. Optimising product design to minimise the number of component parts can effectively decrease assembly-related variable costs. Within a separate additive manufacturing (AM) application, engineers at GE created a novel turboprop engine that was constructed using a mere twelve components, in contrast to the previous iteration which consisted of 855 components[10]. The claimed advantages of additive manufacturing (AM) in terms of quality, flexibility, speed, and cost may perhaps result in significant transformations in operational strategies. Instead of mass manufacturing of a restricted range of items centralised in a few plants, the alternative of regionally dispersed low volume manufacture of highly tailored products is becoming more appealing. Extended to its maximum capacity, geographically dispersed low-volume production has the potential to transform into personal fabrication, where customers can locally print their purchased design upon request. It is plausible that, for certain items, the practices of mass production with limited diversity may be replaced by a strategy of customised manufacture by the masses. Indeed, the whole structure of the supply chain may undergo transformation[11]. Distributed low-volume production of service parts for uptime-critical industrial equipment, such as turbines, provides a strong example for the need of this approach. The need for service parts is characterised by significant unpredictability in terms of scheduling, venue, and necessary parts, resulting in costly inventory storage. The strategic placement of additive manufacturing (AM) machines near assets will facilitate the prompt printing of the necessary service part, leading to enhanced uptime and reduced inventory. The realisation of this ambition is now being achieved, as Siemens asserts its status as the pioneer in the commercial printing of replacement parts on request for big gas turbines [34]. However promising AM is, its current usefulness is limited by numerous notable drawbacks. Quality of a product is not only determined by its complex geometry. Key factors include strength, dimensions, composition, product consistency, and several other attributes. However, AM continues to encounter difficulties in these aspects. Variations in materials necessitate distinct additive manufacturing (AM) methodologies, therefore constraining the adaptability of AM machines and their capacity to manufacture objects using several materials[16]. While the new product development time is rapid, the additive manufacturing (AM) production cycle time is often slower compared to conventional manufacturing methods. Postprocess finishing can function as the bottleneck in this regard. Moreover, while the initial production cost is minimal, the variable cost per part of additive manufacturing (AM) is frequently elevated due to the expenses associated with input materials. Nevertheless, it is important to acknowledge that additive manufacturing (AM) exhibits appeal in terms of sustainability due to its capacity to significantly reduce the amount of material lost during production. The speed and cost constraints are significant factors in large-scale manufacturing, thereby making additive manufacturing (AM) more appealing than traditional methods only for small production numbers. As an example, HP introduced a new additive manufacturing (AM) technology designed for large-scale manufacturing and formed a collaboration with automotive component maker GKN in 2018. The purpose of this collaboration was to use HP Metal Jet in their facilities to manufacture operational metal components for prominent auto and industrial companies, such as Volkswagen [23]. Nevertheless, Volkswagen asserts that the optimal application of 3D printing technology lies not in mass production of automobiles, but rather in the development of specialised components [20]. Indeed, the HP printers are presently designed exclusively for manufacturing cosmetic items, such as customisable automobile key rings and name plates [45]. Given that maintenance and repair operations (MRO) are considered a logical early implementation of additive manufacturing (AM), it has also been a subject of contemporary operations management (OM) study. In their study, Song and Zhang [50] propose a hybrid multipart MRO system that allows for the stocking or 3D printing of spare parts on demand. Their findings indicate that the value of 3D printing is growing in terms of the variety of parts, as calculated by the number of parts, and decreasing in terms of the criticality of the parts, as measured by the outage or backorder cost. In response to a peacekeeping mission conducted by the Royal Netherlands Army and the observation that parts produced by additive manufacturing (AM) in the field may have inferior quality, Westerweel et al. [52] investigate a dual-sourcing service part system. This system allows for the filling of regular spare part orders after a defined lead time, while also utilising AM for the on-demand printing of temporary replacement parts. Knofius et al. [29] investigate the impact of part consolidation potential in additive manufacturing on total lifespan costs, after accounting for spare parts management. Setting aside the concept of AM, the MRO industry has experienced substantial transformation in the last two decades. Original equipment manufacturers, such as Siemens and GE, have shown a strong desire to assume a growing responsibility in the lucrative after-market service sector. The potential consequences of additive manufacturing (AM) on maintenance, repair, and overhaul (MRO) contracting and supply chain architecture are significant and hence, warrant further investigation. The flexibility advantages of additive manufacturing (AM) in terms of initial product line design have been the focus of recent study, beyond the MRO context. In their study, Dong et al. [15] investigates the influence of flexibility economics on assortment planning, specifically on the selection of product variants to offer. Their findings indicate that, when compared to conventional flexible production technologies that incur variable capacity costs due to product variety growth, the implementation of additive manufacturing (AM), which has variable capacity costs that remain constant regardless of variety, results in the firm offering a greater variety of products. Sethuraman et al. [46] investigate the capacity of additive manufacturing (AM) to offer personal fabrication capabilities inside the framework of a monopolistic company that markets a product design to consumers, who may thereafter use AM to manufacture the product according to their desired quality. D'Aveni, a renowned strategic scholar with considerable research and writing on additive manufacturing (AM), asserts that we are approaching a future without assembly, where supply chains are eliminated as all components are produced simultaneously in a single product build-up or printing operation. Undoubtedly, such a future is not devoid of its obstacles. Primarily, firms will encounter challenges in adapting to the new manufacturing paradigm, where the procurement of components and sub-assemblies becomes obsolete, and the research and development department will have absolute authority [7]. Regardless of the imminent realisation of such a future, this vision offers both prospects and obstacles for the academic community to the field of Operations Management[30].

Internet of Things (IoT)

A sensor is a device that detects and/or measures parameters of the surrounding environment and converts its input into an electrical signal that may be manipulated by electronic circuitry. Deloitte University Press's study (Holdowsky et al.[21]) reveals that the mean cost of a sensor decreased by more than 90% from 1992 to 2014 (from $22.00 to $1.40), but microprocessor clock speeds climbed by a factor of 991 (from 29 million to 28,751 million Hz) same period. The convergence of cost reduction and processing speed increase, together with improvements in measurement and communications technologies, has facilitated the concept of a wide range of interconnected sensors on machines, people, and products, together with intelligent controllers, which can respond to real-time sensor data, commonly referred to as the Internet of Things (IoT)[31]. While in the past, decision makers functioned with limited knowledge about the present condition of their relevant environments, the communication between sensor-enabled devices offers the potential to improve the quality and comprehensiveness of the information accessible to decision makers [44]. The term "quality" refers to the degree of accuracy or precision with which a certain nominal characteristic is measured. Completeness refers to the ability to construct system-wide state information by integrating sensor data of specific local characteristics [33]. Significantly, the incorporation of real-time communication in the Internet of Things (IoT) would improve the promptness linked to the quality and comprehensiveness of information. Undoubtedly, the strategic importance of the Internet of Things (IoT) arises from its always improving capacity to overcome the limitation of darkness and generate information without human detection, in various previously imperceptible situations [21]. Based on a McKinsey analysis, the economic influence of the Internet of Things (IoT) is projected to reach trillions of dollars by 2025. Most of this influence is expected to be seen in operational applications related to inventory, maintenance, worker productivity, and optimisation possibilities [32]. The implications for operations projected by McKinsey are not unique. The cornerstone of such projections is constructed on the information completeness, quality, and timeliness provided by the Internet of Things (IoT). This championing of information-driven improvements to inventory management is a reverberation of recent history. The implementation of radio-frequency identification (RFID) tags and readers has the potential to significantly transform the process of tracking and monitoring inventory throughout a supply chain. This is because RFID technology allows for the creation of precise and timely inventory records, without the need for periodic auditing delays, which is not possible with barcoding. Industrial enthusiasm for RFID technology was quickly followed by a significant increase in operations management research that investigated the advantages of precise inventory records and immediate visibility of inventory pipeline development[17]. Evaluating the advantage of perfect inventory information, which is a widely accepted assumption in traditional inventory literature, can be achieved by formulating a policy that considers the inaccuracy or delay of information and then comparing it with a policy that represents perfect information. If precision and promptness of inventory data were the sole operational advantages of the Internet of Things (IoT), then previous studies on RFID technology had already addressed numerous research uncertainties in this area. Although RFID technology contributes to the Internet of Things, sensors1 allow for the collection of far more comprehensive data. Adopting ubiquitous sensors enables a firm to obtain not just immediate and precise data on inventory levels, but also timely and accurate information on the local environment in which any unit of inventory or processing equipment is located. Moreover, the real-time connectivity linked to the Internet of Things (IoT) enables the translation of this abundant local information into comprehensive system-level information. An potential to enhance buffer inventory is identified in the food business through IoT-enabled monitoring of temperature, humidity, and other environmental variables of perishable items across the supply chain [47].

Accurate determination of inventory buffer sizes, while a prominent area of emphasis in the field of operations management research, is not the exclusive responsibility of an operations manager. The real-time implementation, ongoing enhancement, and front-end architecture of the operating system are equally crucial, and the comprehensiveness, excellence, and promptness of information envisaged by the Internet of Things have the capacity to significantly influence these elements. For instance, General Motors use sensors to track humidity levels to enhance the painting process. If the conditions are not ideal, the work item is sent to a different section of the facility [32]. GE perceives the Internet of Things (IoT) as facilitating immediate and continuous improvement, not only within a single facility but also across interconnected networks of assets and facilities, therefore enabling complete optimisation. The objective is to identify the optimal system level solution [12]. Numerous sensors strategically placed across an agricultural field allow for accurate application of herbicides and water, considering the specific circumstances of each parcel within the field or even at the level of individual plants[48]. Condition-based maintenance (CBM) of operational assets, which involves making repair and replacement decisions based on the current conditions of the assets rather than scheduled inspections or unexpected outages, has been extensively studied both practically and academically many years before the Internet of Things (IoT) was developed [53]. Nevertheless, the widespread and interconnected sensors in the Internet of Things (IoT), together with sophisticated predictive analytics, are establishing Cognitively Based Management (CBM) as a crucial field of application in the IoT [53]. The novel advent of digital twins provides a preview of the possibilities of operations facilitated by the Internet of Things (IoT).

As defined [42], a digital twin is a sensor-enabled digital representation of a physical thing that accurately replicates the object in real-time. The essential element in this context is the "live setting"; that is, it is not merely a fixed digital depiction of an object prior to usage, but rather a dynamic expression of the thing that undergoes changes during use. Accurate sensor measurements taken in real-time from several components allow for a comprehensive representation[49] of a sophisticated asset, such as a turbine, or even an entire manufacturing system. The physical world provides a dynamically interconnected representation in the digital realm, and this environment abundant in data can empower operations managers to reveal hitherto undiscovered connections between system conditions and results. This comprehension has the potential to facilitate ongoing enhancement in the reduction of defects, uptime, and other important performance metrics of the current system. Additionally, it can generate more innovative design concepts for future goods and factories, hence improving their producibility. The concept of digital twins is situated at the intersection of physical engineering, data science, and machine learning [18], and this remains applicable to operations facilitated by the Internet of Things (IoT) in a wider sense. Condensing the extensive data produced by sensors into practical knowledge will be a significant hurdle. Real-time, data-driven, system-level optimisation within and across networks of factories and assets will necessitate algorithms capable of solving very big problems with near-instantaneous speed. Challenges of this nature provide abundant research prospects in the field of data analytics and optimisation techniques. Previous studies in Operations Management have thoroughly investigated the significance of inventory information (see to the RFID discussion above) and the utility of sharing forecast information in a supply chain [5, 31]. Hence, considering IoT-enabled processes as inherently rich in information, it may be inferred that the intriguing research enquiries have already been investigated. Undoubtedly, this would be a regrettable outcome. Industrial Internet of Things (IoT) enabled operations will provide a wider range of data that is relevant to production and logistics. This raises questions about the most valuable types of data, the most effective ways to use the data, and the optimal configuration of data ownership in interfirm production systems, such as the servitization of processing assets. Thus, the Internet of Things (IoT) will give rise to a diverse range of research enquiries concerning the development of systems and protocols for overseeing operations and supply chains.

3. Blockchain Technology

Given the vast amount of data presently accessible via the Internet of Things (IoT), there is a need to store this data in a manner that is both easily accessible and secure. A potential resolution to this storage issue is the implementation of blockchain technology. Despite the considerable hype around blockchain technology, there are indeed robust operational applications for the technology [6]. A blockchain is a decentralised and highly secure record-keeping system. The system is distributed in the sense that it can be viewed and written to from any (potentially authorised) endpoint, and its data is kept on a decentralised network. The security of the system is ensured after a block has been appended to the chain, as it becomes immutable and cannot be modified independently. As a ledger, it serves as a repository for information. Digitised currencies, like bitcoin, that leverage blockchain technology are well-known to many individuals. Nevertheless, it is the other applications of blockchain that are expected to be more beneficial for operations managers. A blockchain enables the storage of comprehensive information regarding the complete history of a product as it progresses through the supply chain. While it is possible to achieve this using a centralised database, such as those offered by corporate software solutions like SAP and Oracle, the distributed nature of this approach offers more flexibility. Employing a blockchain eliminates the necessity of granting third-party entry to commercially sensitive systems. Moreover, each participant in the supply chain could contribute information to the chain without requiring a direct affiliation with a centralised "owner." While the information becomes secure once it is part of the chain, there is no assurance that such information will be exclusively posted. The blockchain infrastructure is susceptible to the same "garbage-in-garbage-out" risk as any information system. There is, however, one significant distinction in this regard. Totally digitised information can be achieved with blockchain technology. Stated differently, data from IoT sensors can be automatically uploaded. The accuracy of the sensors directly determines the accuracy of the information stored on the blockchain. Considering the following potential future for the kiwifruit supply chain from New Zealand to China can help to concretise this. Assume that every fruit is automatically affixed with a micro-RFID tag during the picking process. Each instance in which the tag interfaces with a reader, data regarding its location and timestamp is recorded in the blockchain. Furthermore, suppose that, before being packaged, a temperature monitor is affixed to the tray in which the kiwifruit is placed. Subsequently, whenever a reader is encountered (e.g., during the process of loading and unloading from the shipping container), the whole record of the temperatures that all the fruit in the tray have encountered is recorded and published to the respective chains of each fruit. Upon scanning the tag, a Chinese buyer would gain access to a website that converts the blockchain data into practical information. In which location was the kiwifruit cultivated? What is its age? To which temperature extremes has it been subjected? How probable is it go to its ideal edible temperature? Indeed, all the necessary technology to actualise this scenario now exists. The primary challenges would be the proper placement of the micro-RFID during hand picking and the accurate interpretation of the chip by the Chinese consumer. At now, fruits are labelled with individual stickers during packaging, and pallets of kiwifruit are equipped with RFID tags. Consequently, the transition to personalised RFID tags is not a significant leap. Furthermore, while the process of scanning tags may require an increase in phone technology, Chinese customers are accustomed to using rapid response (QR) codes (2D barcodes) to access additional information about a product or verify its purchase. Timely implementation of trace-level QR codes connected to a blockchain is feasible. Described above is an unparalleled degree of knowledge. It would enable much effective management of product recalls. Moreover, it would enhance product safety, especially in the food and pharmaceutical sectors, and reduce instances of fraud. Development of efficient techniques for entering the information has the potential to greatly enhance the accountability of the supply chain. Specifically, it should enable the assessment of whether ethical norms have been followed during the manufacturing and distribution of the product. An additional significant use of blockchain technology, apart from its role in storing information, is the provision of "smart contracts." These contracts are activated automatically in response to externally validated events. As an illustration, payment may be approved immediately upon the container's arrival at customs. Of more relevance is the integration of smart contracts with comprehensive supply chain data. For instance, the remuneration allocated to the kiwifruit transporter may be contingent upon the highest and lowest temperatures encountered by the fruit throughout its transportation. While efficient contracting is a well-established field in operations management, smart contracts appear to provide a myriad of coordination mechanisms that were not before explored.

One more significant advantage of blockchain technology is the eradication of intermediaries. A significant portion of the present function of distributors and goods forwarders is centred around information delivery. Blockchain technology has the potential to virtually eradicate many of those positions. Moreover, should nations adopt the technology, it is possible that customs procedures may be greatly streamlined. Nevertheless, the achievement of these efficiency improvements depends on a certain degree of standardisation throughout the sector. The emergence of several rival blockchains, which is highly probable, and their subsequent proprietaryization, which is a plausible outcome, may result in the loss of numerous efficiencies. Our analysis reveals multiple research prospects arising from the probable influence of blockchain technology on the operations and protocols related to the supply chain. If blockchain technology significantly alters the structure or power dynamics inside supply chains, it becomes necessary to thoroughly examine these novel configurations. Furthermore, as previously said, smart contracts appear to offer a substantial potential for more efficient and advanced coordinating contracts. Furthermore, it should be noted that the scope of data accessible via blockchain technology in the context of the Internet of Things (IoT) is not typically considered in most operational models.

Advanced Robotics (AR)

Manufacturing automation is not a recent development, and artificial intelligence in manufacturing systems is already quite sophisticated. More than 15 years ago, robots at a 40,000-square-meter facility near Mount Fuji, operated by Fanuc, were manufacturing approximately 50 robots per 24-hour shift without any supervision for a period of 10 years. Nevertheless, the technology is progressing swiftly and has the potential to greatly influence industry, agricultural production, service management, and distribution. Conventional robots in the workplace are fitted in protective metal enclosures that ensure physical segregation from workers during regular operations. This is not due to the inherent hazards associated with the activities carried out by robots, such as welding. The reason behind this is that we have not yet equipped robots with adequate cognitive abilities to adapt and make necessary changes in unexpected and fast evolving surroundings. Given the inherent unpredictability of human workers' motions, it is imperative for the robot to exercise strict control and isolation over the work environment. Recent advancements in robotics and artificial intelligence are enabling the deployment of a new cohort of robots in conjunction with human labour. Such collaborative robots, commonly known as "cobots," are now being implemented in actual manufacturing settings. For instance, BMW already employs robots in conjunction with humans on their manufacturing line in Spartanburg, South Carolina, therefore increasing the risk of incurring more severe accidents. Notably, contemporary robots are capable of performing this task with greater speed. However, they pose challenges in terms of programming and installation, and their integration into human production lines is hindered by the associated hazards [6]. Moreover, exoskeletons are being employed to further obscure the distinction between human and robotic labourers. Undoubtedly, the ongoing progress and evolution of collaborative or interactive robots constitute a subject of investigation within the field of computer science and engineering. Examining the adoption, acceptability, and use of robots in manufacturing (and service) environments appears to be the focus of research in the field of Operations Management

(OM), particularly for those interested in behaviour management. The prospect of humans and robots collaborating (which is now to some extent a reality) prompts enquiries on the construction and administration of mechanical systems. Answering these problems necessitates comprehending the perceptions and interactions of workers with robots in repetitive job settings. While somewhat less captivating from a fresh perspective in operations management research, the progress in robotics is also altering the economic advantages of investing in factory automation. Procuring and implementing robots is a highly laborious process. Contemporary home office robots necessitate a team of professionals endowed with the expertise to install (including robots equipped with security systems), calibrate, and ensure their optimal functionality.

Historically, the automation of machining operations has focused on optimising variable costs (in situations when labour is costly), enhancing quality (when robots can outperform people in job repetition), or guaranteeing safety (in cases when the machining centre poses hazards or the activity requires hard physical effort). Due to their high cost and setup durations, robots are well-suited for high-volume, repetitive operations. However, they are not suitable for low-volume or demanding tasks, as robots are prone to repairing or reworking defects and are not easily completed. Recent iterations of robots, created by firms like ABB, iRobot, Motomon, and others, have gotten more affordable and, notably, more customisable to carry out various duties, hence decreasing their frequent redundancy. As inexpensive, customisable, and collaborative robots grow more prevalent, the factories of the future will undergo significant technological transformations. Agricultural robotics is also progressing swiftly. Based on Jordan's [25] findings, almost 60% of the lettuce and 50% of the kale and celery produced at Taylor Farms are obtained using automated methodologies. In addition to harvesting fragile fruits like berries, sophisticated robotics are also employed to assess ripeness, pack, and eradicate weeds. Marketing collaborations including such technology can have resemblance to cooperation within the manufacturing sector. The repercussions of robotics technological progress extend beyond agricultural and industrial sectors. Significant progress has been achieved in machine automation and the utilisation of unmanned aerial vehicles (UAVs). For decades, automated guided vehicles have been employed in industrial settings. Yet, sensors and associated technology have already advanced to the stage where such vehicles may independently and autonomously follow a predetermined course. As an illustration, many students at George Mason University will have an additional choice for their meals: having their food brought on request by automated robots on wheels [22]. Autonomous vehicles are anticipated to exert a substantial influence on transportation and supply networks [36]. Unmanned aerial vehicles, also known as drones, are a swiftly gaining popular robotic instrument. Robotic systems have the capability to monitor distant areas, transport small objects like medicine, monitor assets, and apply chemical sprays to crops. Significantly large drones designed for transporting passengers are also imminent [4]. Drones are employed for the purposes of inventory reconciliation and pipeline inspection, among other applications. They have the potential to facilitate the advancement of novel automobiles [2]. Opportunity for operational management research seem comparable to those for autonomous ground vehicles. To summarise, several technologies have made advancements in terms of cost, adaptability, speed, and/or quality; robotic collaboration plays a crucial role in this regard. Moreover, the selection of automated transportation has the capacity to greatly influence the supply chain operation.

Artificial Intelligence (AI)

Like Industry 4.0, the phrase AI lacks precise definition. Traditionally, AI was characterised as the application of computers to imitate human intelligence. Indeed, it is commonly employed to propose that computers, as opposed to humans, are the ones that solve issues, a perspective that aligns seamlessly with Oblivious Machine theory. Expanding upon the analytics framework, we can categorise corporate intelligence systems as descriptive, predictive, or programmed. Personnel responsible for inspecting, selecting, or defining items must accurately identify and categorise various products. Such can result in cognitive exhaustion, and mistakes can result in flaws or erroneous choice or positioning of objects. Artificial intelligence capable of identifying images or objects might enhance the classification abilities

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of workers or empower robots to efficiently carry out such jobs. As detailed in Section 3, operations enabled by sensors will produce substantial volumes of data that can be analysed using artificial intelligence to reveal past connections between operations and results. This information can then be utilised to enhance design and management procedures. Facial technology has been created in agriculture to facilitate the comprehension of individual cow behaviour by large-stock farmers and small-stock farmers, thereby enhancing milk production [37]. These applications are elucidated by the fact that artificial intelligence (AI) analyses the present condition (of products or social processes) and does not inherently forecast future results or performance. Conclusions can be drawn by forecasting future results and grounding these forecasts on present activities. The significance of predictive AI has grown for firms engaged in fixed assets, such as General Electric and Siemens, since their monitoring processes depend on the accurate prediction of future outages. This necessitates sensors to consistently provide data to the computer, supported by advanced algorithms to calculate the remaining lifespan by considering both present and previous measurements. Artificial intelligence (AI), in which software produces behaviours (or at least instructions), is not a recent development. The existence of manufacturing and decision-making systems (DSS) dates back several decades. What is novel is the growing application of machine learning in the development of these therapeutics. Technological progress in machine learning is also facilitating the growing application of descriptive and predictive intelligence. Generally, operational management models would undertake methodical measures to define targets. When addressing decision-making difficulties, computers employ data learning and statistical approaches to acquire the ability to make sound decisions independently, without depending on an underlying model. Furthermore, there exist hybrid variations of this methodology, in which the algorithm receives some direction but not the complete model (for instance, refer to [19] for a dual-source implementation). [43] asserts that a significant number of top-level executives remain hesitant, even in public, to confront the adverse effects that artificial intelligence (AI) and technology can have on human employees. Within a unique setting, these managers present a distinctive narrative: they engage in competition to maintain their own employees' competitive edge, but they exert less influence on their employees. Indeed, the founder of the Chinese e-commerce business JD.com expressed his aspiration for his company to achieve complete automation in the future. As previously stated, human labour has traditionally been more efficient but still slower than robots. However, the emergence of sophisticated robotics and artificial intelligence is poised to alter this equilibrium. Artificial intelligence offers abundant possibilities for creating techniques for both broad and specialised applications across organisational management study. The intricate nature and magnitude of the challenge, together with the rapidity of its resolution, will be the distinguishing features of forthcoming efforts. From a behavioural standpoint, AI pertains to the dynamic process of human-technology interaction, akin to that of a robot. The growing dependence of employees on recommendations provided by artificial intelligence raises intriguing concerns regarding the management of the human-machine interaction. An expanding body of research in behavioural science [13-14] and organisational management (OM) investigates algorithmic avoidance and the interplay between human agents and decision support systems (DSS). Specifically, Caro and Saez de Tehada [18] and Sun et al. [51] shown that adherence to Decision Support Systems (DSS) may be somewhat lower, but can be enhanced by modifying their presentation or algorithmic procedures. In general, we anticipate that AI will exert a substantial influence on a range of operations and delivery functions.

Additional Technologies

Although our primary emphasis is on fundamental technologies like additive manufacturing, IoT, blockchain, advanced robotics, and artificial intelligence, there are many other developing technologies that are exerting considerable influence on Industry 4.0. Augmented reality (AR) is the integration of digitally produced visual or other sensory information into the physical world. This technology has broad applications, extending beyond entertainment to include economic sectors. General Electric (GE) is utilising augmented reality (AR) to enhance production and efficiency by transmitting work instructions to facilities and employing sensors to oversee assembly and ensure workers are well-informed. Upon encountering an issue, the system promptly alerts the operator or guides them to the subsequent action [27]. Furthermore, while Google Glass is not now accessible for consumer usage, wearable augmented reality glasses are already being used in production. A worker can remotely scan Google Glass to gain insight into its functionality. The user will be presented with a map, image, or video of their preference. Additional applications for electronic devices encompass gadgets specifically engineered to mitigate physical and mobility injuries, as well as devices specifically developed to monitor and record worker exposure to explosives. The progress of technology and artificial intelligence has led to the emergence of novel advancements in material science. These include thin, robust, transparent, and very efficient graphene materials, as well as a smart material capable of regulating its qualities in reaction to external feedback. Furthermore, apart from the progress made in wearable technology, it has the potential to facilitate the development of intelligent goods tailored for use in production and industrial processes. Furthermore, Agriculture 4.0 encompasses specialised agricultural machinery and the production of high-quality food. For instance, vertical farming and genetics are two significant technologies in this domain. Furthermore, there is a growing favourability for experimental and bio printed animal and plant proteins. The Agricultural technology sector (inclusive of protein, food, seed, and crop technology) received $25 billion in venture capital in 2015. The China Agricultural Development Bank has committed a minimum of 3 trillion yuan ($435 billion) by 2020 to upgrade China's agricultural industry.

FINDINGS OF THE STUDY

Based upon the data collected and analyses the following major findings could be found.

Technological Integration is Uneven across Manufacturing Sectors

While large-scale manufacturers are beginning to adopt Industry 4.0 technologies such as AI, IoT, and robotics, small and medium enterprises (SMEs) are lagging behind due to limited resources and technical expertise.

Significant Operational Improvements Observed

- Organizations that have adopted Industry 4.0 report improvements in efficiency, production flexibility, real-time monitoring, and product customization.
- Automation and data-driven decision-making are reducing waste and downtime in operations.

Disruption of Traditional Trade-offs

Industry 4.0 challenges traditional assumptions in operations management:

1. For instance, high quality and flexibility no longer necessarily lead to high costs, due to intelligent automation and real-time data analytics.
2. Speed and cost-efficiency are being achieved simultaneously in digitally transformed organizations.

Major Challenges Still Inhibit Full-scale Adoption

Key challenges identified include:

1. High initial investment and unclear ROI.
2. Lack of skilled workforce capable of handling cyber-physical systems.
3. Cyber security concerns and data privacy issues.
4. Interoperability problems between legacy systems and new technologies.
5. Resistance to change at both management and workforce levels.

Readiness Levels Vary Widely

1. Many firms express interest in Industry 4.0 but lack the infrastructure and policy support to adopt it effectively.
2. There is a gap between awareness and implementation, especially in developing regions.

Need for Strategic and Collaborative Efforts

Adoption success is higher in organizations that have:
1. Clear digital transformation roadmaps.
2. Invested in employee training and change management.
3. Formed collaborations with tech providers, academic institutions, and policymakers.

CONCLUSION

The relationship established between the business and the equipment entails competitive benefits like price, flexibility, speed, and quality. Although all these factors are significant, the company must prioritise its top four focus and decide among them. All business strategies, such as those focused on customers and their values, facilitate the business in making this decision. The prioritisation order directs the development and construction of the physical operational architecture, including factors such as the level of vertical integration, design capacity, transportation and MRO system assets, and the distribution zones for different types of products. An operational and supply chain architecture is a framework in which intangible processes and procedures govern the movement of products and commodities. As previously illustrated, the technologies that underpin Industry 4.0 have the potential to enhance one or more of the four fundamental domains, either independently or in conjunction. Significantly, Business 4.0 has the potential to alleviate some of the pressure on crucial and lucrative clients. Industry 4.0 fundamentally establishes a novel framework for strategic business architecture and associated operations. Advancements in technology, such as the Internet of Things, will have a direct influence on the management of operations and supply chains, and will also indirectly affect the selection of real estate. Others may have a direct influence on architecture, but their effect on the process is merely indirect. The advent of Industry 4.0 is expected to significantly influence the field of architecture and the methodology of ideation. Cost-effective additive manufacturing and easily configurable robots decrease the minimum scale needed for commercial production and enhance the efficiency and speed of initiating production. Integrated robotics, artificial intelligence, gadgets, and augmented reality can augment (or obviate) the function of human resources. The integration of the Internet of Things, blockchain technology, and digitisation could facilitate the instantaneous remote monitoring, control, and optimisation of assets in both industrial and field settings. A global, decentralised, agile network of manufacturing assets capable of rapidly and flexibly adapting and modifying operations is feasible. There is a widespread belief that the integration of the physical and digital realms in Industry 4.0 will significantly influence operations and supply chain management. The operations management community should become part of this vision in order to comprehend the consequences and constraints of Industry 4.0 and contribute to the development of strategies and technologies that facilitate its potential and implementation. We anticipate that this publication will prove valuable to organisational management researchers who are investigating the potential and obstacles within this domain.

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